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Understanding and Predicting Foam in Anaerobic Digester

I. R. Kanu, T. J. Aspray, A. J. Adeloye

Abstract—As a result of the ambiguity and complexity surrounding anaerobic digester foaming, efforts have been made by various researchers to understand the process of anaerobic digester foaming so as to proffer a solution that can be universally applied rather than site specific. All attempts ranging from experimental analysis to comparative review of other process has not fully explained the conditions and process of foaming in anaerobic digester. Studying the current available knowledge on foam formation and relating it to anaerobic digester process and operating condition, this piece of work presents a succinct and enhanced understanding of foaming in anaerobic digesters as well as introducing a simple method to identify the onset of anaerobic digester foaming based on analysis of historical data from a field scale system.

Keywords—Anaerobic digester, foam, biogas, surfactants, wastewater sludge.

I. INTRODUCTION

FOAMING has been a continuous and threatening problem amid the various challenges experienced in the operation of anaerobic digester (AD). AD foaming is highly unpleasant with potential loss of active digester volume, structural damage, spillage, damage to the gas-handling system and subsequent reduction in biogas production. In general when foaming occurs in AD, it tends to reduce the production of gas by up to 40% [10]. This was illustrated in a survey by the American Society of Civil Engineers reporting half of all ADs to have experienced foaming at least once during their operating lifetime [6]. A further survey of foaming in ADs in wastewater treatment plants in USA carried out from April to August 2011 showed that out of the 39 plants surveyed, 32 had experienced foaming in the past five years or were presently undergoing foaming [16]. The identified causes included: presence of foam causing filamentous microorganisms, fats/oil/grease (FOG) and feed sludge quality [16]. A similar survey carried out in Spain showed, out of 38 plants that responded to the survey, 23 of them had experienced foaming with the causes being attributed to sludge characteristics and operating factors [13].

Several researchers have investigated AD foaming with reports that do not represent a systematic study of foaming

occurrence [7]. Some of these studies were either based on heuristic knowledge from site operators or inferred knowledge from foaming reports in other biological systems. For example, [11] carried out a comparative review of foam formation in biogas plants and ruminant bloat. Reference [7] related the wider knowledge of a well-studied problem of biological foaming in activated sludge process to provide useful information on understanding the process of foaming in AD. A review of mechanistic multidimensional knowledge by [17] was used to analyse AD foaming with the aim of developing a better relationship between AD foam characteristics to process and operational factors. Notwithstanding these scholarly works, there still exist some opacity on the influence of AD process/operating conditions on foam formation and stabilisation in AD. Hence, in this study, a further effort was channeled towards clarifying the uncertainty surrounding foam initiation and stabilisation by studying current reports on foam formation in biological systems and relating it to AD operating conditions. In addition, a simple and novel method to monitor the onset of AD foaming was developed by statistically analyzing historical data from a foaming and non-foaming anaerobic digester.

II. FOAM

Most foam occurs as a medium of gas trapped in thin fluid film with or without particles and may be represented as a solid in three dimensions with flat polygonal faces (films), straight edges (plateau) and sharp corners or vertices (Junctions) [8], [18]. Film is the most obvious feature of a foam and separates the gas bubbles which are forced together to form the foam. The films meet along a line or curve known as the plateau borders. These are interstitial channel filled with liquid that meet at junctions to form an interconnected network. Understanding this intricate foam structure is essential in appreciating the dependency of changing aspects of foam from formation to stability/collapse on a microscale fluid flow and macroscale motion of foam bubbles making up the foam structure [15]. Thus, foam can further be classified based on how easy the foam is generated and the extent to which it could remain stable before it collapses to liquid. Consequently, foam can either be stable, metastable or unstable [3], [8], [20].

In subsequent paragraph, we will be looking at factors that affect foam formation and stabilisation as well as relating such conditions to what is prevalent in AD.

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A. Foam Formation

Gas-liquid-particle mixtures (such as those found in AD) will foam only when surfactants are present to lower the surface tension of the liquid and trap gas bubbles as they blow up. Thus, chemically pure liquids do not foam. Usually, the developed foam is made up of about 80% gas. Everyday foaming experience ranges from soap bubbles to beer bubbles as it is poured into a glass. In each case there is presence of, liquid (surfactant) and bubbles (gas).

B. Foam Stability

Foam stability and collapse are very crucial in foam life as they determine the intrinsic qualities of foam. It is difficult to explain foam stability separately from foam collapse as they are two inevitable conditions. This means that, foam when formed will either stabilise or collapse. Basically, foams are unstable and will likely collapse to a liquid which is its lowest energy state [8]. This usually occurs because foam film though seemingly stable, will burst at hundreds of centimeters per second, initiating a visible rearrangement of bubble assembly through surface and fluid forces occurring over less than a second [15].

It has been noted by [8] that the intense adsorption of surfactants at the walls of the bubble opposes the collapse of foam. The surfactants adsorb on the bubble walls as they are both hydrophobic and hydrophilic. The hydrophobic sect which often has an organic structure tends to move away from the fluid while the hydrophilic group which is either polar or have charges that separate when dissolved in water moves toward the fluid forming [8]. In addition, an increment in surface tension is observed whenever a film is suddenly stretched locally (such as mixing), resulting in increased opposition to the destabilising force [18].

Coarsening is the gradual change of the foam structure due to gas diffusion through the films which is dependent on pressure differences between bubbles. Small bubbles have high pressure and disappear quickly as they lose gas to bigger bubbles. As this happens, average foam size increases with time as foam coarsens.

The ratio of liquid content to foam is very important when considering foam stability. Liquid fraction in foam can range from zero to about 35%, the wet limit, at which the bubbles come apart [18]. Whenever there is a set amount of liquid in the foam, it tends to drain due to the influence of gravity and local variations in pressure through films, Plateau borders and junctions of the static foam structure. This is in accordance with the hydrostatic pressure law necessary for equilibrium under gravity and also depends on the type of surfactant dominating in the liquid [8].

Disjoining pressure is essentially the mutually repulsive force between two faces of a film which opposes further thinning. The film thickness at which equilibrium is achieved is determined by the balance between the disjoining pressure and the bulk pressure of the liquid. The disjoining pressure increases as distance between the films decreases while the bulk pressure decreases to large negative values as the liquid fraction of the foam decreases [18]. Thus, if thinning is

opposed, then the rate at which the foam collapse declines. On the other hand, the presence of particles has been shown to accelerate foam collapse as shown in Fig. 1. Reference [8] found that fluidized solid particles are at zero order, thus acting as stationary objects over which liquid could pass. In addition, solid particles increase the effective density of the gas bubble thereby compelling the gas to rise at a faster velocity causing a decrease in gas holdup as buoyancy is proportional to the difference between the gas density and the density of the liquid plus solid mixture [8]. This provides less time for emulsification of the bubbles by surfactants resulting in less foam formation and stability.

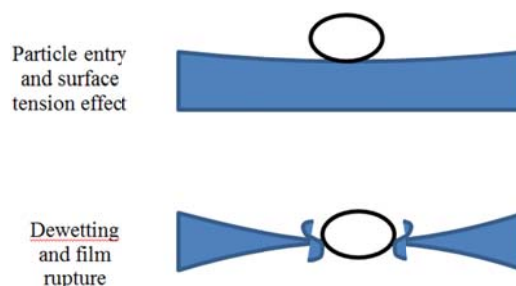


Fig. 1 Effect of solid particles on foaming

III. ANAEROBIC DIGESTION BASICS

Reference [1] pointed out that the energy in sewage (thermal, chemical and mechanical) is 2-4 times the amount of energy employed in treating it and thus should be adequately harnessed using anaerobic digestion. Anaerobic digestion (ADN) is a multi-stage biochemical process which stabilises organic matter in an environment devoid of oxygen using anaerobic micro-organisms. A well-functioning digester will reduce the volume of waste while producing biogas made up of predominantly methane (~60%) and carbon dioxide (~40%), as well as, impurities such as hydrogen sulphide, moisture and siloxanes [18].

TABLE I
MOLECULAR WEIGHT AND DENSITY OF MAJOR GASSES PRESENT IN ANAEROBIC DIGESTER

Gas	Formula	Molecular weight	Density(kg/m ³)
Ammonia	NH ₃	17.031	0.769
Carbon dioxide	CO ₂	44.01	1.977
Hydrogen	H ₂	2.016	0.0899
Hydrogen Sulphide	H ₂ S	34.076	3.74
Methane	CH ₄	16.043	0.717
Nitrogen	N ₂	28.02	1.165

During anaerobic digestion, intracellular/extracellular enzymes produced by different types of microorganism bacteria act as facilitators while, solid retention time (SRT), hydraulic retention time (HRT), alkalinity, absence of toxic substances, bioavailability of nutrients/trace elements, pH, temperature and gas concentration play very significant role in ensuring the process efficiency [4]. In Table II, the ideal range for these operating parameters is enlisted as target.

Amongst the operating factors, the digester retention time is very important as it form the basis for sizing ADs to ensure

sufficient stabilization of the system. Calculation of SRT is centered on the mass of solids in the digester and the mass of digestate removed daily while HRT is calculated based on the volume of AD and digestate removed daily. SRT equal HRT if supernatant draw off is not done [5]. In terms of toxicity, the process of anaerobic digestion could be very sensitive to certain compounds, such as sulfides, volatile acids, heavy metals, calcium, sodium, potassium, dissolved oxygen, ammonia, and chlorinated organic compounds at various concentrations. Most of these inhibitory compounds are not issue of great as they occur at a very low concentration in wastewater activated sludge.

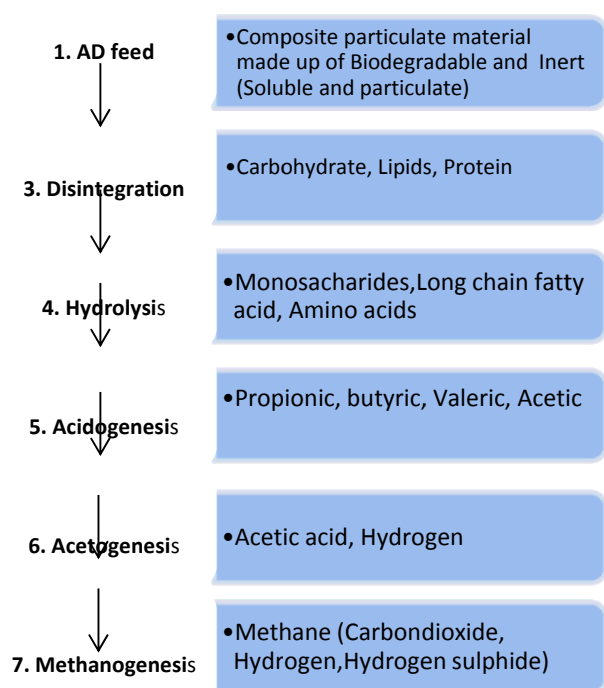


Fig. 2 Anaerobic digestion biochemical process

As shown in Fig. 2, for an AD set up in a municipal wastewater treatment plant, the composite particulate material are usually Primary Sludge (PS), Secondary Sludge (SS), and a combination of both with or without the addition of organic waste (codigestion) [2], [5]. To ensure a higher volatile solid reduction, disintegration a non-biological process of breaking down lumps of composite particulate material could be deployed. This can be achieved through energy application in the form of ultrasound, heat, pressure or in combination. The methods include; ultrasound treatment, thermal hydrolysis, pasteurisation and homogenisation [19].

During hydrolysis, relatively pure substrates are broken down by the help of extracellular enzymes to particulate amino acids, monosaccharides and long chain fatty acids (LCFA). The acidogenic bacteria break down monosaccharide and amino acids to mixed organic acids, hydrogen and carbon dioxide. These are further acted upon by acetogenic bacteria that act on LCFA, propionic, valeric and butyric acids to convert them to acetate, hydrogen and carbon dioxide. With

additional activities of hydrogen utilising methanogenic and acetoclastic methanogens, methane is formed [4]. Reference [14] pointed out that since methane formers are more sensitive to environmental factors and more difficult to reproduce; its activities are easily inhibited. This compel the design and operation of AD to best suit the requirements of the methanogens. Hence, most ADs are designed as mesophilic (30–38°C) with several other types of AD based on modification of operating conditions. To ensure that the digester is running at optimal capacity, the conditions listed in Table II must be maintained. This can be achieved by frequent monitoring of the system to ensure compliance. Reference [5] noted that monitoring the trend in variation of these conditions to assist in making vital decision about the digester operation is more crucial compared to obtaining a single increase or decrease in the value of the operating conditions.

TABLE II
MAJOR CONDITIONS FOR MESOPHILIC DIGESTER TO FUNCTION OPTIMALLY

Parameter	Target	Rate	Sample location
Temperature (°C)	32 - 38	Daily	Digestate
Volatile acids (VA) (mg/ L)	50 - 330	Daily	Digestate
Alkalinity (mg/ L)	1500 - 5000	Daily	Digestate
VA:Alkalinity	0.1 - 0.2	Daily	Not required
pH	6.8 - 7.2	Daily	Sludge feed
Total solids (%)	Monitor the trend	Daily	Sludge feed
Volatile solids (VS) (%)	Monitor the trend	Daily	Sludge feed
Organic loading rate (kgVS/m ³ d)	1.6 - 3.2	Daily	Sludge feed
Gas production (m ³ / kg of VS destroyed)		Daily	Gas storage
Gas composition	< 35% CO ₂	Daily	Gas storage

IV. FOAMING IN ANAEROBIC DIGESTER

Reference [7] defined AD foaming as a buildup of a mixture of gas bubbles bounded by liquid films on the surface of the sludge while in activated sludge wastewater treatment process, microbial foam appears as a dark brown viscous layer [12]. Formation of foam is one of the major causes of process upset in biogas plants [19]. No one knows the exact cause of foaming as sludge and digester design is a unique combination and presents a unique set of circumstances with foaming occurring under the best of circumstances [21]. However, foaming is considered excessive if it blocks piping and/or escapes the containment of the anaerobic digester (AD) [19]. The tendency for a foaming episode to constitute nuisance is dependent on the stability of the foam. As can be seen from Fig. 3, the first column on the right is experiencing stable foam as there is a gradual and sustained foam level for a long period of time. On the contrary, metastable foaming is taking place in the second column by the right with foaming level not rising nor reducing so rapidly. Obviously, unstable foam had taken place in the two left columns as shown by the solids left on the glass walls as the foam collapsed. This foaming potential test presented in the picture is a typical representation of the possible occurrence of foam in ADs.



Fig. 3 AlkaSeltzer® foaming potential test

V. MECHANISM OF FOAM IN ANAEROBIC DIGESTER

Drawing knowledge from the literature on foam, we will now try to understand AD foaming. Foaming will occur when gas bubbles through liquid containing surfactants with or without the presence of some solid particles. By virtue of AD process, gas bubbles, liquid and surfactants are intrinsic properties of the system. Thus, as anaerobic digestion progresses, biogas produced will rise to the top due to density difference and are trapped within the aqueous solution made up of surfactant (detergents entering the works) and bio surfactants (produced by microorganisms during the digestion period) forming foam. Usually, AD foam has a specific gravity of 0.7 to 0.95 and contains a lot of solid particles. [5] However, the nature of the foam and the operating conditions in AD determines whether a foaming nuisance will arise.

Ideally, AD releases sufficient gas resulting in increased hydrodynamic interaction between adjacent foamed bubbles due to an increase in disjoining pressure compared to the bulk pressure. Subsequently, foamed bubbles break to release gas at the top of the digester. On the contrary, when the digester is not functioning optimally as a result of deviation from one or more of the conditions stated in Table II, there is insufficient production of gases, then the hydrodynamic interaction between neighboring bubbles tend to reduce, resulting in more emulsified bubbles moving to the surface of the digester forming a layer of foam.

At optimal AD operating conditions, the ratio of methane to carbon dioxide produced is higher. Table I shows that methane has lower density and smaller bubbles compared to other gasses that methane make up the AD biogas. Reference [9] found the solubility of methane in mesophilic conditions in the digester to be one-twentieth of that of carbon dioxide with the coefficient of diffusion of methane to be 4.5 times greater than that of carbon dioxide. Consequently, coarsening effect makes it easier for methane gas bubbles which are smaller to be released faster from the foam trap than other gas components. On the contrary, when the digester is going sour, the acid formers (which release carbon dioxide) work much more quickly than the methane-forming microorganisms resulting to

an increase in carbon dioxide production which is bigger and not released easily from the foam. This results in foam stability developing into a foam nuisance.

Viscosity affects the stability of foam as it is the extent to which a fluid resists a tendency to flow by another fluid. Considering that foaming is likely to occur at the wet limit of 35% [18], this means that for the digester not to attain a state of nuisance foaming and allow the flow of produced biogas to the headspace and down to the gas storage, AD should be operated at an optimal organic loading rate to ensure that adequate viscosity is maintained in the digester. This will allow for foamed bubbles to drain easily as well as avoid the accumulation of excess sludge in the digester that will incapacitate the available biomass. This supports the idea by most researchers that the most common cause of digester foaming is organic overload which is attributable to intermittent digester feeding, separate feeding or inadequate blending of primary sludge and WAS; insufficient or intermittent digester mixing; and excessive amounts of grease or scum in digester feed (especially problematic if the digester is fed in batches) [5]. When AD is subjected to organic overload, the digester content is more viscous and there is production of more VFAs than can be converted to methane, at such circumstances, the acid formers (which release carbon dioxide) work much more quickly than the methane-forming microorganisms producing more carbon dioxide.

VI. FOAM PREDICTION

Based on the preceding discussion, we can conclude that emulsification of gas bubbles by liquid containing surfactant (foaming) is a regular occurrence within the aqueous phase in the AD and is dependent on biogas produced, surfactant and liquid concentration. Since surfactant concentration is not easily determined in AD as observed in an on-going experiment, it can be related to the digester feed as greater percentages of surfactants found in AD are released as biosurfactants by biomass during the hydrolysis stage of anaerobic digestion.

Therefore,

$$\text{Foaming potential} = \frac{\text{Volume of biogas produced}}{\text{Volume of feed to the digester}}$$

Using this formula and applying historical and analytical data from two full scale digesters, one with a foaming problem and one without, it was found that the ratio was above 20 for non-foaming digesters and below twenty for foaming digesters. This is possibly a quick way for operators of biogas to determine when the digester will likely foam. In addition, adequate monitoring of the system using the parameters listed in Table II will go a long way in alerting operators of likely foam events. Emphasis should be on proper sampling and regular analysis.

VII. CONCLUSION

A detailed study of foam formation, and stability has enabled a better understanding of anaerobic digester foaming and has assisted in developing a novel method to predict the

onset of foam formation by effectively monitoring the anaerobic digester process and using values obtained from the monitoring process to determine foaming propensity.

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